EXCIMER LASERS FOR DEEP UV LITHOGRAPHY

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Abstract

Krypton Fluoride excimer laser-based wafer steppers are now expected to extend optical microlithography to sub-0.5pm design rules in VLSI chip fabrication. The performance and operational requirements for the excimer laser for this application are very stringent and different from conventional excimer lasers. For practical reasons, the stepper requires that the spectral bandwidth of the laser be reduced to less than 3pm, while the wavelength is stabilized to better than +/-0.5pm. This paper will discuss these issues and the design features of such an excimer laser. This paper also addresses issues relating to the integration of this laser with a wafer stepper and operation in a wafer fabrication environment.

Introduction

Optical lithography continues to be governed by the basic resolution and depth of focus parameters expressed in the formulas below. These basic formulas show the ability to improve image resolution by reducing the exposure wavelength, increasing the numerical aperture of the imaging lens, and by decreasing the process K-factor.

The imaging wavelength used in photolithography is shifting from the traditional G-line (436nm) to I-line (365nm) and excimer (248nm and 193nm) emission lines. The numerical aperture component of the foumula is also changing with the availability of lenses with higher N.A. values. Finally, the development of new resist materials with higher resolution permits the K process factor to decrease, thereby increasing overall resolution potential.

Using the basic formula for resolution and depth of focus shown in Figure 1, optical lithography with short

wavelength sources, high numerical aperture lenses and low process K-factor (mask bias, resist, etch factor, etc.) has the potential to extend photolithography to sub-half-micron, and eventually quarter-micron levels. These levels of resolution are required in the production of 64Mb and 256Mb DRAM devices.

RESOLUTION $R = K_1 \frac{\lambda}{NA}$

DEPTH OF FOCUS: $DOF = K_2 \frac{\lambda}{(NA)^2}$

K_1, K_2 - Empirically Determined Process Coefficient

- $K_1 \sim 0.6 - 0.8$; $K_2 \sim 1.0$

λ - Exposure Wavelength

NA - Numerical Aperture of Imaging Optics

Figure 1: Resolution and Depth of Focus for an Optical Imaging System

The major imaging source emmision lines along with the practical limit of numerical aperture and resolution for two k-values are shown in Table 1. Note that even with the conservative K-factor of 0.8, resolution can migrate to 0.4um using the excimer laser at 248nm for lens with 0.5NA. The development of practical surface-imaging resist processes will permit even smaller k-values, possibly below 0.5 using silylation or similar processes where the dependence of focal depth is relaxed considerably. The limits of optical resolution, based on these factors, are estimated below.

Limits of Optical Resolution

Refractive Lens	Practical Limit of N.A.	Resolution L/S (um)	
		k =0.8	k =0.5
g-line(436nm)	0.65	0.54	0.34
i-line(365nm)	0.60	0.49	0.30
KrF(248nm)	0.50	0.40	0.25
ArF(193nm)	0.50	0.30	0.19

The pathway to sub-quarter micron optical lithography using excimer lasers as the light source is now emerging as a clear direction, and the technology issues and problems are being solved on the first 20-30 prototype laser steppers now in use worldwide.

This paper will focus on the excimer laser light source being used in these wafer stepper systems. The basic design, operation, and production aspects will be covered, including the safety, stepper interface, and maintenance issues.

Laser Requirements

The excimer laser for production lithography must meet a set of requirements ranging from optical parameters (wavelength, bandwidth) to facility considerations (installation, safety, stepper interface). The basic laser operational requirements are summarized below:

Excimer Laser Specifications for Deep UV Reduction Stepper*

	1st Generation	Production
o Center Wavelength	248.1 - 248.5nm (absolute accuracy <+/- 3pm)**	248.1 - 248.8
o Spectral Bandwidth	3pm (FWHM)***	<2pm
o Spectral Energy Distribution	>90% Energy in 10pm	>95% in 5pm
o Wavelength Stability****	<+/- 1pm	<+/-0.15pm
o Output Power	2-5 Watt	6-8 W
o Repetition Rate	>200 Hz	>/=400Hz
o Pulse Stability	<+/-10%	<+/-3%

* Refractive Optics
** pm = 0.001 nm
*** FWHM: Full Width at Half Maximum
**** Focal Plane Change; 0.16um for 1pm shift in Center Wavelength

The center wavelength is determined primarily by the natural photon emmision from an excited krypton fluoride molecule; the narrow spectral bandwidth of the laser is required to meet the overall resolution specification of the wafer stepper, and for compatibility with the fused silica stepper lens. Only fused silica has the wavelength transmission properties required in a deep UV wafer stepper lens.

The control system of the laser must additionally keep the wavelength and pulse energy stable in order to meet the focus and exposure specifications of the wafer stepper. Output power determines the amount of energy available for wafer exposure, and along with repetition rate, contribute significantly to wafer stepper throughput.

In order to meet the requirements of the I.C. fab line, the laser must conform to industrial safety standards, have low maintenance, service and operating costs, and provide a relatively small footprint.

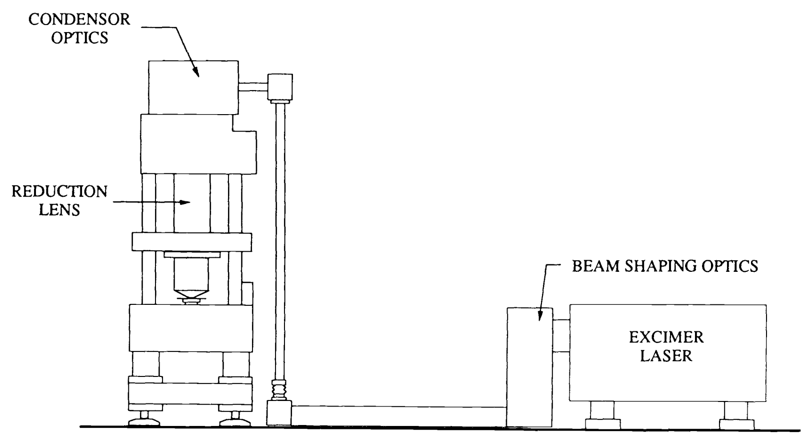

Figure 2: Excimer Laser Stepper Configuration

The laser runs at 3-4 atmospheres pressure, and uses a low concentration (0.1%) of fluorine gas. The efficiency of the laser is high due to special inert materials used in the discharge chamber, allowing cryogenic processing to be eliminated. This simplifies laser operation and reduces cost. The efficiency of the pre-ionization system of the laser is high, keeping operating voltage low, and thereby improving reliability and reducing maintenance intervals. A schematic of the discharge chamber of the laser is shown in Figure 3.

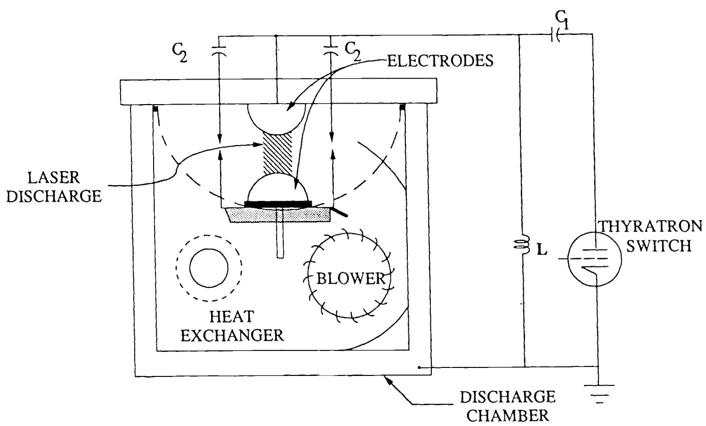

Figure 3: Schematic of Laser Discharge Chamber

The laser uses water cooling, and a blower to circulate the excimer gas mixture rapidly and uniformly across the electrodes. A metal-fluoride trap is used to remove particulates (metal fluoride dust) from the laser gas, and special electrode design and choice of materials for internal chamber parts help insure uniform wear and good, stable beam profile, and increased lifetime.

Laser Sub-Systems

The excimer is divided into several key sub-systems. The main sub-system is the laser 'head', consisting of the discharge chamber and metal fluoride trapping system based on an electrostatic technique. The discharge chamber consists of the electrode structure, preionizer, heat exchanger, blower and windows.

The electrical energy transfer system is also a major sub-system, consisting of the pulse power module (main capacitor, thyratron, peaking capacitors), thyratron support module, and high voltage power supply.

Another sub-system is the optical resonator. This consists of the line narrowing module (rear of the laser), partial reflector (output coupler, front), the wavelength and energy diagnostic module, and the basic structure onto which these modules are mounted for maximum stability.

The control system of the laser consists of the power distribution system, computer, I\O controller, and stepper-laser interface module. Additional modules include the gas handling system, blower controller and power supply, interlocks, cooling system, and diagnostics.

External to the laser is the vacuum pump out system, fluorine trap, emergency off module, laser support structure/enclosure, and ventilation system. A schematic of the entire system is shown in Figure 4.

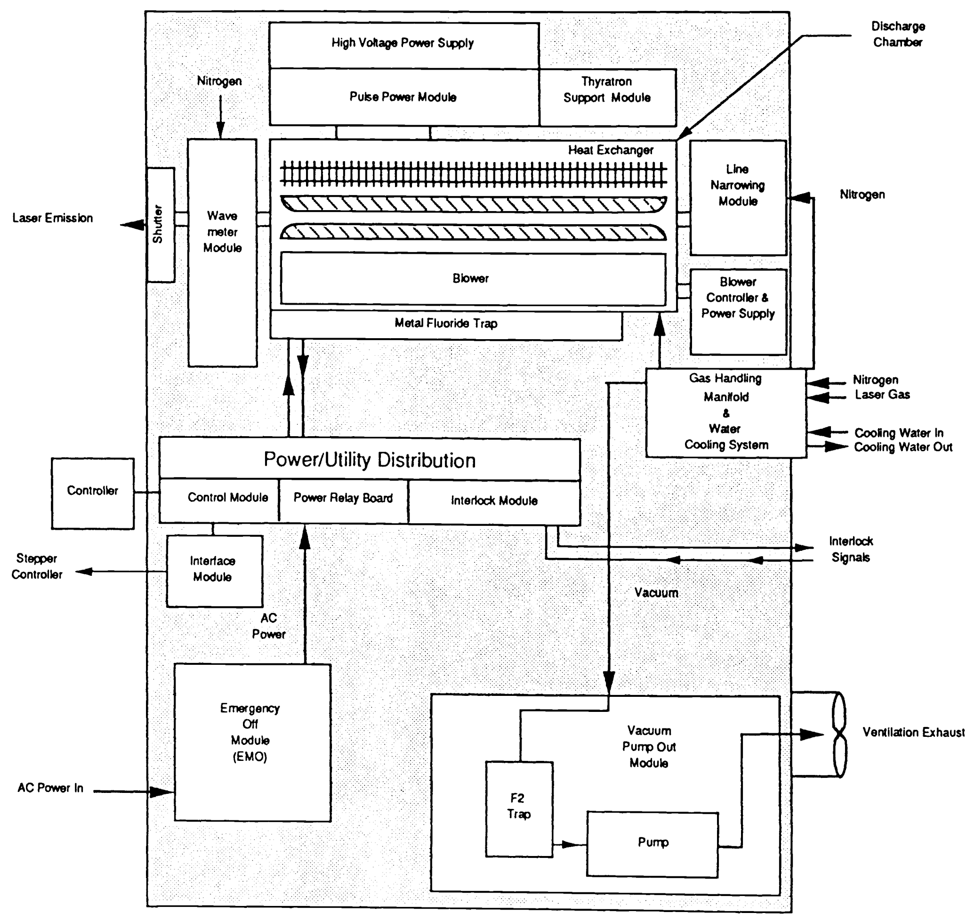

Figure 4: Excimer Laser System Schematic

Spectral Narrowing

Spectral narrowing of the laser is required in order to be compatible with the fused silica stepper lens (since chromatic correction is not possible with fused silica) and to meet the resolution and depth of focus specifications of the stepper. There is no chromatic correction needed if a narrow spectral bandwidth is used with a refractive optics system. A line narrowing module in the laser spectrally narrows the laser bandwidth to less than 3pm, with over 90% of the energy within a 10pm band. The relative bandwidth stability is <+/-0.5pm, and the tunability range is >+/-300pm. In general, line narrowing can be achieved using etalons or a grating.

Etalons (based on selective transmission as a function of wavelength) have high efficiency but are thermally unstable, having high drift and long stabilization time. Gratings (where angular selection is a function of wavelength) are somewhat less efficient, but are thermally very stable and have a high damage threshold. Figure 5 shows a schematic of line narrowing techniques.

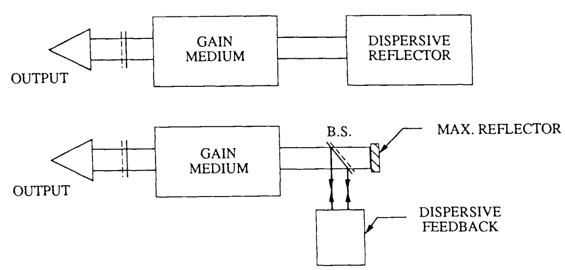

Figure 5: Line Narrowing Techniques

Wavelength Stabilization

In order for the wafer stepper to maintain its focus specifications, the laser must achieve control over the wavelength stability. The wavemeter in the laser must be able to measure wavelength to an accuracy of less than +/-0.5pm or less, and control long term drift to the same value or less. Also, bandwidth measurement resolution must be less than 1pm, and bandwidth measurement accuracy of +/-0.5pm. Finally, the wavemeter needs to be relatively insensitive to changes in ambient temperature or pressure, and provide a high speed computational algorithm to measure relative wavelength.

Wavemeters based on etalons are most suitable for meeting these requirements. An etalon-based wavemeter is calibrated with an atomic reference source, as shown in the schematic in Figure 6. The coarse etalon tracks the wavelength within a 200pm range, and keeps the system from getting lost, i,e, rolling over to another wavelength. The fine etalon tracks the wavelength within 20pm (1 free spectral range), and a dedicated microcomputer tracks the location of the fringes down to the pixel level centered on a photodiode array. After initial calibration of the wavemeter in the factory, the system is relatively stable, and need only be re-calibrated periodically against an absolute reference (atomic line for Fe) source.

The microcontroller in the wavemeter remembers the frequency position, and after brief standby periods, will frequency lock back to the set position within approx. 40ms. Since a photodiode measures every individual pulse, the system will rapidly make any minor correction at the outset of the pulse train, and lock on the pre-set wavelength.

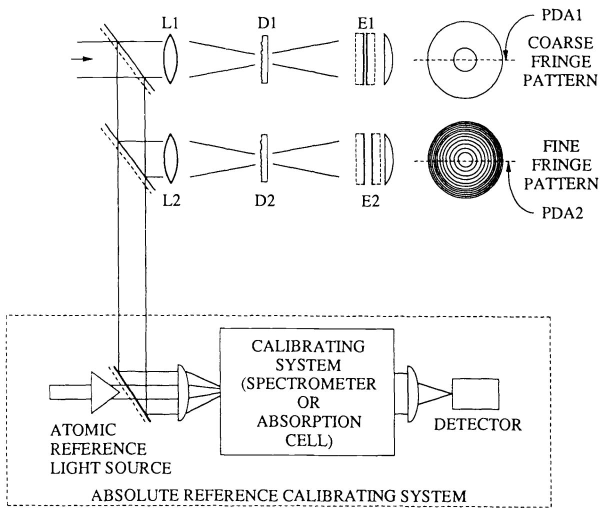

Figure 6. Wavemeter Based on Etalons and a Typical Fringe Pattern

Stepper and Laser Interface

In many I.C. fab areas, it is desirable to keep as many major sub-systems as possible in the chase area, minimizing traffic in the clean room. The ability to 'pipe' the laser beam across a relatively long distance permits easy installation of the laser in the chase area, as shown in the

schematic in Figure 7. In this diagram, the laser computer is interfaced to the stepper computer system. The output beam is processed through an optical module, where it can be shaped and homogenized before transport into the stepper lens. Light uniformity requirements of 2-3% across the entire wafer exposure area are needed to achieve the necessary resolution levels.

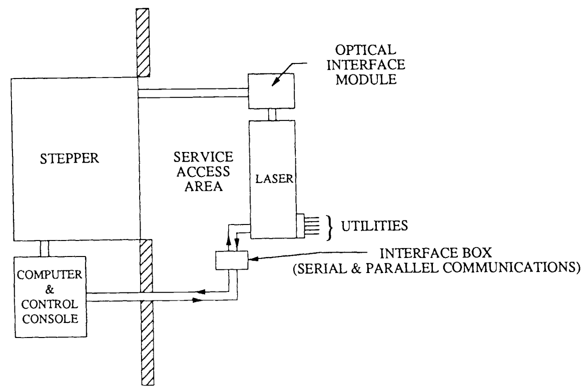

Figure 7: Stepper/Laser Interface

Lifetime and Maintenance

There are two basic levels of scheduled maintenance needed to keep the laser operating within its specifications in production. The first level involves two relatively simple procedures: cleaning the laser windows and replacing the metal fluoride trap. These procedures (about 1 hour each) can be scheduled in parallel with other preventative maintenance needed on the stepper, and therefore need not contribute to downtime. Laser windows can survive many individual cleanings before needing to be replaced, and the metal fluoride trap can be refurbished or cleaned as well.

The second level of maintenance occurs after several hundred million pulses have accumulated on the laser, an interval that typically represents several months. At this point, the laser chamber is replaced (modular), the vacuum pump oil is inspected and replaced if needed, the fluorine trap is replaced, and the overall system is inspected and calibrated if needed. These maintenance procedures can likewise be scheduled in parallel with standard maintenance/calibration needed on the wafer stepper itself, thereby maximizing uptime of the system. Service time required for this second level of maintenance is about 12 hours.

Installation and Safety

The laser described in this paper has met industry standards for electrical, radiation and gas safety, including many local codes which are often more stringent than state or national codes. The installation requires plumbing to vented cabinets containing the laser gases and purge gas (helium). House nitrogen is also used to purge the laser optics and operate the pneumatic valves. Water lines provide cooling to the laser, and an exhaust vent (4-6 inch, 200-400 cfm) purges the laser enclosure to protect the operators in the event of a leak. Ventilation is also provided at every plumbed gas connection.

Safety interlocks are located at appropriate points, and the beam path is completely shielded and interlocked. The laser is required to meet CDRH requirements. The gas lines are double-walled co-axial stainless steel, and all exhaust gas is processed through a fluorine trap. The high voltage modules are enclosed, and proper grounding used on these enclosures. Special insulating materials are used to conform to electrical wiring codes, and devices to provide safe discharge of circuits prior to servicing are built to be 'auto' setting. Figure 8 shows the laser with gas lines and basic installation plumbing in place.

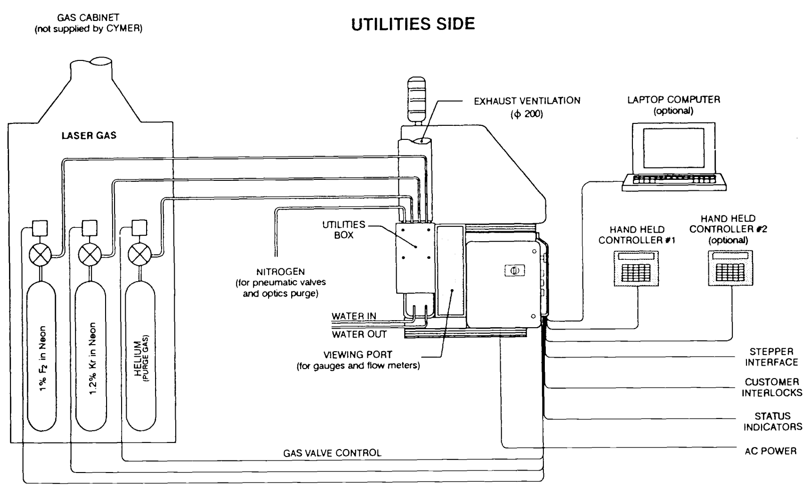

Figure 8. System Facilities Configuration

The Future: Overall Areas for Improvement

Some key activities required to make excimer lithography fully compatible with production manufacturing requirements include the following:

1. Complete characterization of the laser stepper with 248nm-sensitive resist systems.
2. Higher level integration of the laser stepper in the I.C. fab line; improved laser/stepper integration.
3. High duty-cycle life testing of the laser and stepper to improve reliability.
4. Performance improvememts in the laser: bandwidth reduction, increased power, lower operating costs, reduced scheduled maintenance.
5. Lenses with increased numerical aperture.
6. Development of a high-speed, surface-processable excimer resist system for 248nm.

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Summary

A spectrally narrowed and wavelength stabilized krypton fluoride excimer laser for microlithography has been discussed specifically relating to its role with a deep UV wafer stepper in producing 64Mb and 256 Mb dram devices. The overall requirements for using the laser under production conditions in an I.C. fab have been addressed, as have details concerning the operation of this laser under these conditions. Future improvements to further adapt the laser to I.C. production lithography are reviewed.

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